

PRINCIPAL TYPES OF FOUNDATIONS

5.1 SHALLOW FOUNDATIONS

A *shallow foundation* generally is defined as a foundation that bears at a depth less than about two times its width. There is a wide variety of shallow foundations. The most commonly used ones are isolated spread footings, continuous strip footings, and mat foundations.

Many shallow foundations are placed on reinforced concrete pads or mats, with the bottom of the foundation only a few feet below the ground surface. The engineer will select the relatively inexpensive shallow foundation for support of the applied loads if analyses show that the near-surface soils can sustain the loads with an appropriate factor of safety and with acceptable short-term and long-term movement. A shallow excavation can be made by earth-moving equipment, and many soils allow vertical cuts so that formwork is unnecessary. Construction in progress of a shallow foundation is shown in Figure 5.1. The steel seen in the figure may be dictated by the building code controlling construction in the local area.

Shallow foundations of moderate size will be so stiff that bending will not cause much internal deformation, and such foundations are considered rigid in analyses. The distribution of stress for eccentric loading is shown in Figure 5.2a, and bearing-capacity equations can be used to show that the bearing stress at failure, q_{ult} , provides an appropriate factor of safety with respect to q_{max} . The equations for the computation of bearing values are presented in Chapter 7.

Shallow foundations can also be designed to support horizontal loads, as shown in Figure 5.2b. Passive pressure on the resisting face of the footing and on the surface of a key, along with horizontal resistance along the base



Figure 5.1 Construction of a shallow foundation in progress.

of the footing, can be designed to resist the horizontal load. Active pressure would occur on faces moving away from the soil, but these may be ignored as being too small to make any difference in the solution.

Factors that influence the selection of a shallow foundation are discussed in Chapter 1. Usually shallow foundations are less expensive than deep foundations, but designs become more complicated as the foundation becomes larger in plan. Significant stress for a mat or larger shallow foundation reaches deeper soils, and the computation of deformation becomes more complicated than for the foundation of moderate size. Not only will the vertical movement

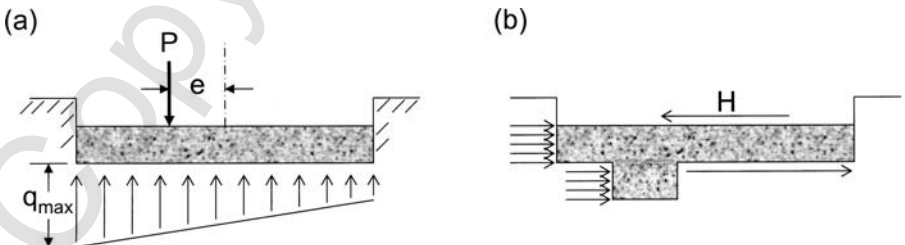


Figure 5.2 Elevation views of shallow foundations. (a) Bearing stress for a foundation under eccentric vertical loading. (b) Stress distribution for a shallow foundation under horizontal loading.

be larger than for a footing, but the deformation of the mat must be considered as well as the deformation of the supporting soil.

The principal problem with shallow foundations under light to moderate loading concerns expansive clay, discussed in Chapter 6. The problem is widespread and can be devastating to homeowners. Engineers must be especially diligent in identifying expansive clay at a building site and taking appropriate actions if such soil is present.

5.2 DEEP FOUNDATIONS

5.2.1 Introduction

Typical types of deep foundations are discussed in the following paragraphs. Entrepreneurs have developed several special and innovative types of deep foundations, and more will continue to be offered by the construction industry. Only one of the special types is discussed below.

Professionals associated with a particular project will make an appropriate study leading to the selection of the particular type of deep foundation. Such a study involves factors related to the structure, subsurface conditions, local practice, and special requirements. For example, the authors worked on a project where deep foundations were to be installed near an elementary school. The noise level was the overriding consideration. The contractor could work only when the school was not in session or had to use a drilled foundation with a noise level lower than would occur during pile driving. The engineers selected the drilled foundation.

Omitted from the presentation that follows is a consideration of deep foundations that may be used for soil improvement, such as sand piles or stone columns.

5.2.2 Driven Piles with Impact Hammer

The engineer frequently makes an extensive and thorough investigation prior to selecting of the type and configuration of a pile for a particular project. The pile must sustain the expected loadings with appropriate safety, and construction must be accomplished in a timely manner while complying with local regulations. In some cities, for example, noise is a major concern and regulations may preclude the use of many driven piles. The types of piles and the factors affecting the selection of a particular pile are noted in the following discussion.

Several later chapters address methods for computing the axial and lateral capacity of a pile. The piles may be timber, reinforced concrete, prestressed concrete, structural-steel shapes, steel pipe, or a tapered-steel pipe. The engineer selects the pile type and hammer on the basis of (1) loads to be supported, (2) tolerance of the superstructure to differential settlement, (3)

expected life of the project, (4) availability of materials and construction machinery, (5) length of time required for installation, (6) difficulty of construction, (7) ability to make a proper inspection, (8) noise during construction, and (9) cost.

Environmental effects on the material composing the pile must be considered. Steel in some environments will be subjected to corrosion. In offshore practice, some piles may extend through the *splash* zone, where corrosion must be considered. Two procedures are common: extra-thick steel may be provided to account for progressive loss of the steel with time or a form of cathodic protection may be provided. Timber piles can be treated with creosote to prevent attack from insects, but this does not prevent damage from certain species of marine borers (Grand, 1970). And, as discussed below, special care must be employed in driving reinforced concrete piles to prevent cracking that could lead later to failure due to corrosion of the rebars.

The engineer may need to consider the *drift* of driven piles during installation. The tips of the piles in a group may move close to each other at full penetration and may actually touch each other during driving. The bending stiffness of the piles relative to the stiffness of the soil and the position of the head of the pile are factors that affect the drift. The closeness of the piles after installation may or may not affect their ability to sustain loading. If the final positions of the piles in a group are important, the engineer may stipulate that preboring be employed.

A large variety of impact hammers are available up to the size required for driving very long piles and down to the smallest that can be driven. Hammers may be drop-weight, diesel, single-acting steam, or double-acting steam.

The structural engineer and the geotechnical engineer may cooperate in studying the relative advantage of a small number of larger piles and a large number of smaller piles. The selection may be dictated by local construction practice.

With the preliminary selection of a pile, an appropriate computer code should be employed in matching the hammer and cushioning to the pile. The cushioning material may be some form of plastic, or wood of various sorts. Plywood sheets are frequently used as cushioning. The computer code models a compressive wave yielding stress versus time, generated by the impact of the hammer, taking the cushioning into account. The wave travels down the pile and is reflected at the pile tip. For driving against bedrock, a compressive wave is reflected. For driving against very weak soil at the tip, the wave is reflected as a tensile wave. Tension in a reinforced concrete pile can cause cracking that could result in penetration of water, leading to corrosion. Some reinforced concrete piles under bridges have been so damaged due to tensile cracks as to need replacement.

The proper cushion is important. The authors were asked to review a project where the cushioning was provided by sheets of plywood. The plywood

was replaced irregularly and actually caught fire on occasion. The result was cracking of some of the reinforced concrete piles due to compressive forces.

One of the authors participated in driving an instrumented, closed-ended steel pipe with a diameter of 6 in. A blow from a drop hammer caused the pile to move down in soft clay but with very little permanent set. Persistent driving was damaging the instrumentation, and the decision was made to use a coiled spring from a rail car as the cushioning. The pile drove readily, with no damage to the instrumentation. The decision to use the soft cushion was made by judgment, but the implementation of a computer code to model the pile driving would have been useful.

An impact hammer resting on a driven pile is shown in Figure 5.3. A continuous-flight auger is shown that can be used to predrill a small-diameter hole to a given distance to ease the driving into some formations. The photograph shows disturbance to the soil in the vicinity of the pile, which must be considered when computing pile capacity. Vibrations and soil movement due to pile driving can cause severe damage to existing structures and has been investigated in detail (Lacy and Gould, 1985; Lacy and Moskowitz, 1993; Lacy, et al, 1994; Lacy, 1998).

Some piles are driven with vibratory hammers, principally steel sheet piles used for retaining structures. Bearing piles are installed with vibratory techniques in some soils, and vibratory methods are frequently used to pull casings that were installed for the construction of drilled shafts. Vibratory hammers are less noisy than impact hammers and can result in less movement of the soil when driving into some sands.

5.2.3 Drilled Shafts

The design and construction of drilled shafts are discussed in detail in many publications (e.g., Reese and O'Neill, 1988). Drilled shafts (called *bored piles* in some countries) are constructed by predrilling a cylindrical excavation while keeping the excavation from collapsing by appropriate means, placing a rebar cage, and then filling the excavation with concrete. A typical drilling rig for constructing drilled shafts is shown in Figure 5.4.

The drilling machine may be mounted on one of three types of carriers: a truck, a crane, or a crawler. The smaller machines are truck-mounted and may move readily along a public road. The soil-filled auger is visible on the truck-mounted machine in Figure 5.4, and spinning will dislodge dry soil. Excavations for light loads may be made with diameters as small as 12 to 18 in. and to depths of a few feet. Excavations for massive loads may be made with diameters of 15 ft or more and to depths of 200 ft. The drilled-shaft industry provides technical information and training through the International Association of Foundation Drilling (ADSC) in Dallas, Texas.

The engineer develops an appropriate design by sizing the drilled shaft for a particular application, but significant effort is necessary in preparing of specifications for construction. The engineer who made the design and prepared the specifications should manage the field inspection. Drilled shafts are



Figure 5.3 Impact hammer atop a driven pile.

a popular type of deep foundation, but as with other deep foundations, special care must be taken by the engineer to ensure proper construction.

Drilling machines are fitted with powerful engines to drive a rotary table and kelly. A variety of drilling tools are available. The appropriate drilling tool operating with downward force from cables or with a weighted drill string can be used for drilling into rock. Rock sockets are common to accommodate design requirements, giving the drilled shaft an advantage over some other types of deep foundations.

The following sections describe three types of constructions in common use, but the details of each may vary with the contractor. The specifications for construction prepared by the engineer must be prescriptive in some in-



Figure 5.4 Construction of a drilled shaft with a truck-mounted unit.

stances (e.g., giving the required slump of concrete for the particular job) but should lean toward the performance desired from the drilled shaft. Prescribing a particular construction method is usually unwise because anomalies in the soil profile could lead to the use of a wet method even though the dry method appeared feasible at the outset.

Dry Method of Construction The dry method of construction may be employed in soils that will not cave, slump excessively, or deflect inward when the hole is drilled to the full depth. A type of soil that meets these requirements is stiff clay. The water table may be located in the stratum of clay, and above the water table the clay may be saturated by capillarity. A problem occurs if the clay below the water table contains fractures that allow water to flow into the excavation. If such fractures were not observed in the soil investigation, the dry method of construction may have been specified and then may have become impossible to achieve.

The steps in employing the dry method of construction are shown in Figure 5.5. A crane-mounted drilling machine is positioned as shown in Figure 5.5a. The location has been surveyed and staked to give the contractor precise information on location and on the final position of the top of the shaft. Specifications will inform the contractor about tolerance in placement and in deviation from the vertical as the shaft is advanced. A temporary surface

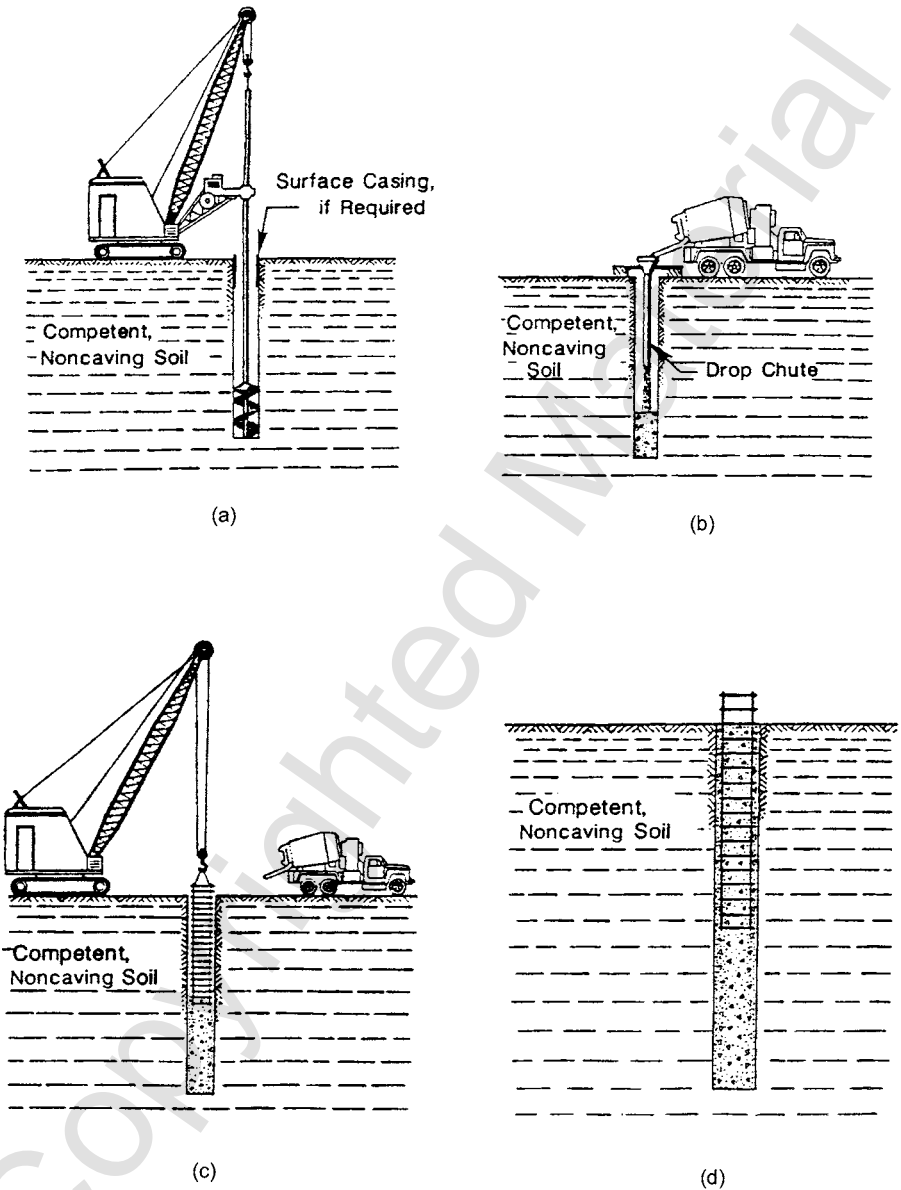


Figure 5.5 Dry method of construction of a drilled shaft: (a) start of drilling; (b) placing concrete of bottom of shaft with a drop chute; (c) placing partial length rebar cage; (d) completed shaft (from Reese and O'Neill, 1988).

casing is frequently placed after the excavation is advanced a few feet. The surface casing prevents raveling of the soil at the surface and provides a positive guide for inserting the auger as drilling proceeds.

Figure 5.5b shows concrete being placed in the bottom of the excavation, where the computed stresses in the drilled shaft show that no reinforcing steel is needed. Specifications almost always state that the concrete must be poured without striking the sides of the excavation or any obstruction to prevent segregation during placement, and the drop chute serves to guide the concrete in free fall. Research has shown that concrete may fall great distances without segregation if no obstruction is encountered during falling.

The placement of the rebar cage is shown in Figure 5.5c, and the final concrete is placed by use of a tremie or by pumping. Guides are placed on the rebar cage to ensure centering. A service crane is required to hold the tremie or the pump line, as shown in the figure. Alternatively, the crane with the drilling machine could do the work, but further drilling would be delayed. Specifications frequently require that the concrete be placed the same day the excavation is completed to prevent time-dependent movement of the soil around the excavation. The completed shaft is shown in Figure 5.5d.

Casing Method of Construction The casing method of construction may be employed where caving soils are encountered, as shown in Figure 5.6a. Slurry, either from bentonite or polymer, is introduced when the caving soil is encountered and when drilling proceeds through the caving layer and into cohesive soil below. The casing is placed, and the bottom is sealed into the cohesive soil. Prior to placing the casing, the slurry is treated to remove excessive amounts of inclusions and to ensure that specifications are met for properties of slurry before placing concrete. The contractor twists and pushes the casing to make a seal that prevents the slurry from entering the excavation below the casing.

Figure 5.6b shows a crane-mounted drilling unit inserting a drill through the casing and drilling into the cohesive soil below. The excavation below the casing is smaller than that used in the initial drilling, and the difference in size, not as great as indicated in the figure, must be taken into account in computing the geotechnical capacity of the shaft. Figure 5.6c shows that an underream has been excavated at the base of the excavation and that the casing is in the process of being retracted. The fluidity of the concrete and the retained slurry are very important. The concrete must be sufficiently fluid that the excavation will be completely filled and the slurry will be ejected from the excavation. The cleaned slurry must be free of inclusions and easily displaced from the excavation by the fluid concrete. Specifications address the desirable slump of concrete and the characteristics of the slurry.

Figure 5.6c shows the slurry at the ground surface. Preferably the slurry is directed to a sump, where a pump sends the slurry to a tank for cleaning and reprocessing. The disposal of the slurry must meet environmental standards. Slurry from polymers is usually much more easily disposed of than slurry from bentonite. The completed shaft is shown in Figure 5.6d.

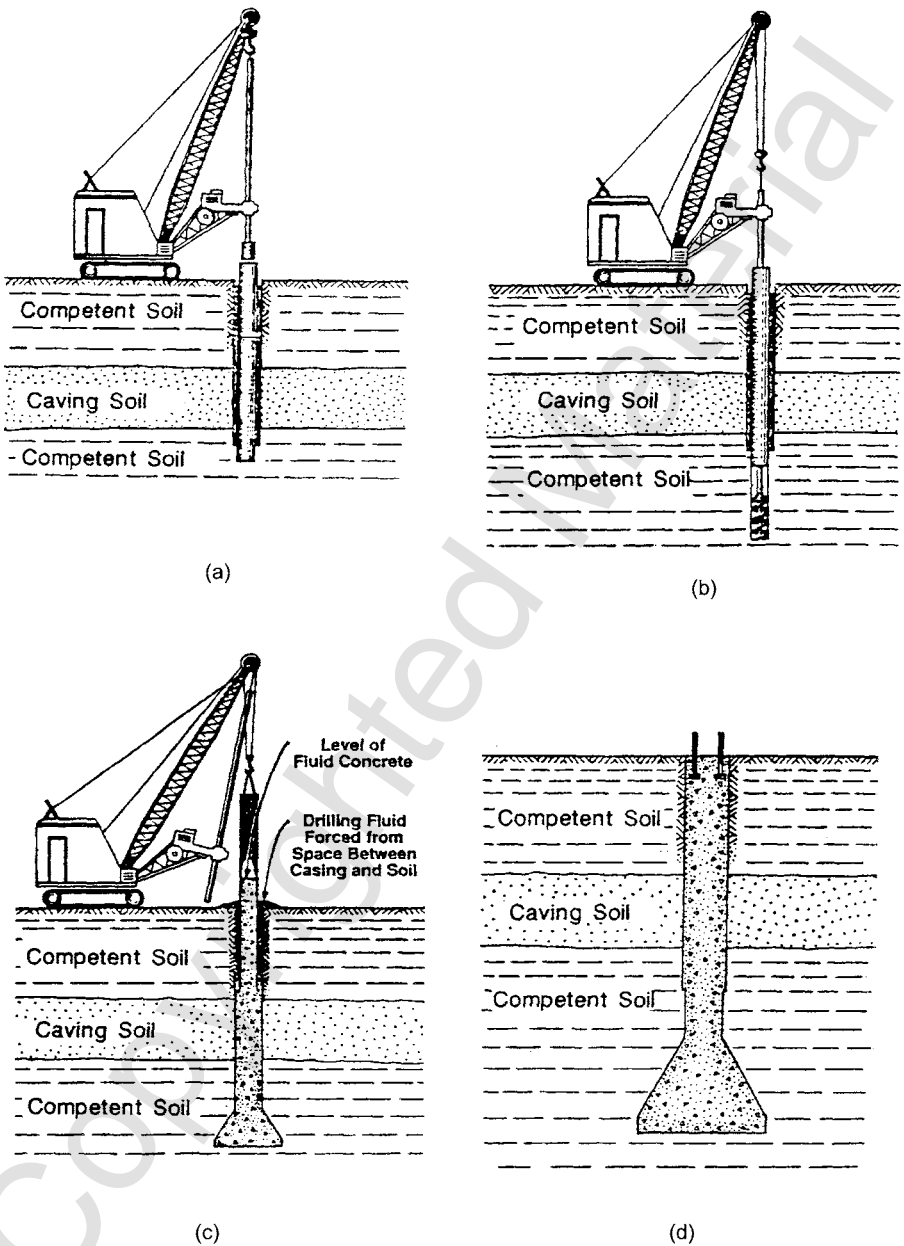


Figure 5.6 Casing method of construction of drilled shaft: (a) slurry used to penetrate caving soil and casing placed; (b) smaller auger used to drill through casing; (c) casing retrieved after drilling underream; (d) completed shaft (from Reese and O'Neill, 1988).

Wet Method of Construction The wet method of construction permits the rebar cage to be placed into a drilled hole filled with fluid. As with the casing method, the drilling fluid is slurry, as shown in Figure 5.7a. The excavation is made to the full depth with slurry, with the contractor exercising care to keep the height of the column of fluid in the excavation above the water table. The slurry acts to create a membrane at the wall of the excavation in the caving soil, usually a granular material, and any flow of fluid will be from the excavation into the natural soil.

The rebar cage may be placed directly into the fluid column, as shown in Figure 5.7b. Prior to placing the cage, samples of the slurry are taken from the excavation, with most samples taken from the bottom, where suspended particles collect. Not shown in the figure is the system for pumping the slurry from the excavation, directing the pumped fluid to a container, usually a tank, where the slurry can be cleaned with screens and centrifuges if necessary. Specifications are available from the owner of the project or from standard specifications regarding such characteristics as the sand content of the slurry, the pH, and the viscosity. The aim of the specifications is to ensure that no debris will collect at the bottom of the excavation to interfere with load transfer in end bearing and that no slurry remains along the sides of the excavation to interfere with load transfer in skin friction.

The placing of the concrete is shown in Figure 5.7c using a tremie and a concrete bucket. The bottom of the tremie is sealed with a plate that detaches when the tremie is charged fully with concrete. Alternatively, a plug is placed in the tremie to separate the concrete for the slurry and moves downward as the concrete is placed in the tremie. The plug, perhaps made of foam rubber, is compressed and remains in the concrete or floats upward in the column of fluid concrete. The completed shaft is shown in Figure 5.7d.

Plain water can sometimes be employed as the drilling fluid. One of the authors worked at a site in Puerto Rico where the founding stratum was a soft rock with joints and cracks. The water table was high, and drilling dry was impossible. Water was employed as the drilling fluid, and the level of water in the excavation was kept above the water table to prevent inward flow and possible weakening of the founding stratum.

5.2.4 Augercast Piles

Augercast piles (also known as *augered-cast-in-place* piles) are constructed by turning a continuous-flight auger with a hollow stem into the soil. On reaching the desired depth, grout is pumped through the hollow stem as the auger is withdrawn, forming a column of fluid grout. A short rebar cage can be set by gravity or sometimes by the use of vibration. In addition, if desired, a single rebar can be placed in the hollow stem before grout is pumped. These piles are termed *continuous-flight-auger* (CFA) piles in Europe and have received wide acceptance there and elsewhere.

Among the construction problems that have been encountered with the use of augercast piles are the sudden retrieval of the auger, allowing the soil to

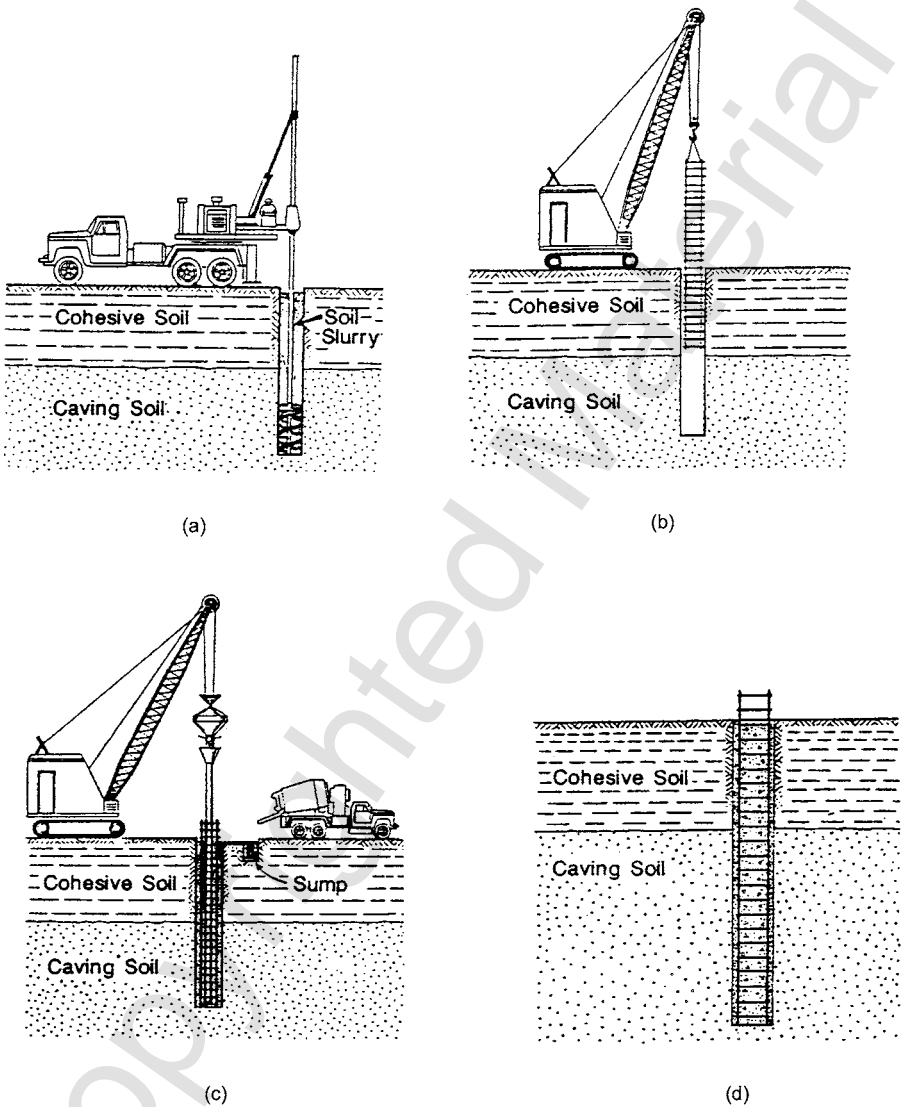


Figure 5.7 Slurry method of construction of a drilled shaft: (a) drilling into caving soil with slurry; (b) placing rebar cage; (c) displacing slurry with fluid concrete; (d) completed shaft (from Reese and O'Neill, 1988).

squeeze in and cause a neck in the pile; the continued rotation of the auger after it reaches the desired depth, with the result that soil is “mined”; and upward flow of water around the sides of a pile or through the center opening when installations occur where the water table is high. The mining of soil during drilling by an unqualified or careless workman can lead to a collapse of the ground surface in the area around the pile. Some problems can be eliminated by the use of instruments on the drilling machine. Such instruments produce a record showing the rate of rotation of the auger as a function of depth and the amount of grout that is pumped as a function of the depth of the auger.

Loss of ground due to mining of subsurface soils is more of a problem when constructing an augercast pile in sand than in clay. Some engineers are reluctant to specify the use of augercast piles in sand unless careful inspection is programmed.

A potential problem with augercast piles is possible eccentricity during the application of loading (Siegel and Mackiewitz, 2003). This problem may arise because of the lack of reinforcement except for the short cage near the top of the pile and a single bar along the axis.

Lacy et al. (1994) have discussed the use of augercast piles to reduce or eliminate the impact on adjacent structures. Driving piles will cause vibration that can affect nearby structures and can also cause the settlement of deposits of loose sand that can potentially cause great damage to structures in an urban setting. Augercast piles have proved to be very useful in some settings, but construction must be monitored carefully to ensure a sound and competent foundation.

One of the authors has observed the use of CFA piles in the overconsolidated clay near London. The drilling rigs are invariably instrumented, and axial-load tests are frequently performed at a site to prove the quality of the construction and to confirm the results of the analyses of axial capacity. The system for testing the pile is often controlled by a computer, and the working load can be confirmed by maintaining the load overnight or longer without the presence of a technician.

5.2.5 GeoJet Piles

The GeoJet pile is described as an example of a special kind of deep foundation. Numerous kinds of special deep foundations have been developed and employed in some projects. The engineer faces the problems of designing for the support of axial and lateral loading and of preparing specifications for construction that allow for inspection to ensure good quality. With regard to design, the properties of the soil will be affected by the method of installation. Therefore, the engineer must depend heavily on the results of load tests with the special foundation at the site or as reported in the technical literature where all relevant details are presented.

The GeoJet pile is constructed by rotating a special drilling head into the soil and introducing grout through the drilling head during withdrawal. Figure 5.8 shows a typical drilling head attached to a kelly prior to initiating construction at a site. If construction conditions are favorable, the column of soil cement can be constructed in less than 5 minutes. After the column of fluid soil-cement is created, a steel insert, such as a pipe, is placed to the full depth of the pile by gravity with minor driving. Tests of samples of soil-cement made with the soil from the construction site lead to the desirable percentage of cement to give the soil-cement the necessary strength and the desirable percentage of water so that the steel insert can fall under its own weight. The concept employed in construction is that sensors in the system will provide data to a computer on the specific gravity of the grout, the amount of grout being pumped, the measurements of pressures at points in the system, the



Figure 5.8 Drilling head used in construction of the GeoJet pile.

rate of rotation of the auger, and the force encountered in drilling. A printed record may be made showing relevant data as a function of depth. The record is valuable in evaluating the quality of the construction.

Some data have been collected on load tests with piles constructed by the GeoJet system, but the concept of design is that pile tests are performed at a site with designs of soil-cement based on the tests noted above. Some data have been collected on GeoJet piles that have been tested (Spear et al., 1994; Reavis et al., 1995).

5.2.6 Micropiles

Micropiles are deep foundations with a small diameter. They may be installed in a variety of ways and have several purposes. Bedenis et al. (2004) describe the use of micropiles as load-bearing elements to strengthen foundations that were to support a greater load. The piles were installed by drilling, and were employed because pile-installation equipment could not be operated in the available space inside the building. The piles consisted of a high-strength steel bar with a diameter ranging in size from 32 to 63 mm, grouted into place, and forming a pile 152 mm in diameter. The piles extended through overburden soils to sandstone at a depth of 24.7 m. The capacity was developed principally through side resistance in the sandstone.

Gómez et al. (2003) describe the testing of a micropile with a diameter of 219 mm and a length of 7.13 m, consisting of a central casing with a diameter of 178 mm that was embedded in grout. The soil at the test site consisted of 3.0 meters of residual soil above rock. The instrumentation revealed that the bond between the rock and the grout did not fail, but some loss of load transfer in skin friction was noted as the movement of the pile relative to the soil increased above 0.05 mm.

If micropiles are used to sustain compressive loads, the engineer should compute the buckling load by using a computer code. The unfactored lateral load should be applied, and the compressive load is increased in increments until failure occurs by excessive lateral deflection. Pile-head fixity must be modeled as well as possible or the analyses should be performed with a range of pile-head fixities that encompass the value to be anticipated.

5.3 CAISSONS

Caissons are often used as foundations for bridges, and may be large in cross section and seated deep beneath the mudline. While the sides of the excavation will be in contact with soil, the caissons may be designed as end-bearing units if the founding stratum is bedrock or strong soil.

Shuster (2004) gives an example of the construction of a caisson in discussing the foundations for the new Tacoma Narrows Bridge. Steel boxes, 18 ft high and 8 by 130 ft in plan, were lowered to the sea bed at a depth of

150 ft. Concrete lifts with a height of 15 ft were added to the top of the steel boxes as they were lowered. Dredging was done within the cells of the caisson until the bottom reached a depth of 60 ft.

5.4 HYBRID FOUNDATION

A hybrid foundation consists of both a soil-supported mat and piles and is used principally to support an axial load. In Europe it is commonly called a *piled raft* because engineers conceived the idea of designing the foundation for high-rise buildings using a mat (raft) resting on the ground with piles supporting the mat (Figure 5.9). The concept was that the combined foundation would be sufficient to support the applied axial loading with an appropriate factor of safety and that the settlement of the combined foundation at working load would be acceptable. The settlement of a mat foundation is

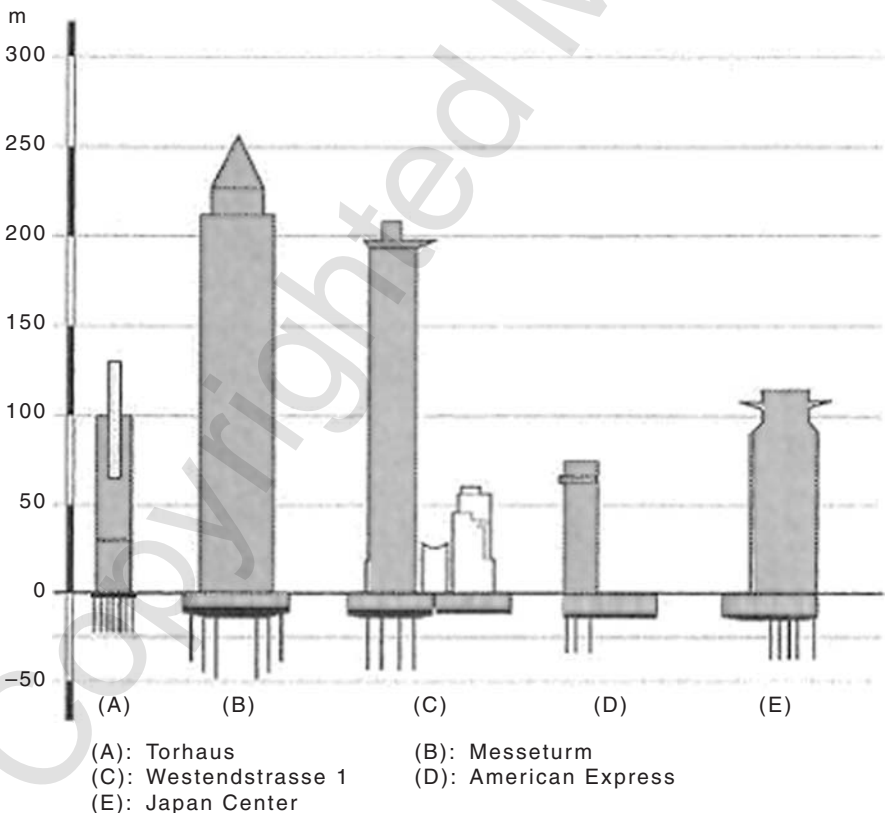


Figure 5.9 High-rise buildings in Frankfurt with piled raft foundations (after El-Mossallamy and Franke, 1997).

dish-shaped, with the largest settlement at the center of the mat. To achieve a more uniform settlement of a structure, it has been suggested that the piles be clustered near the center of the mat.

The analysis of such a system is complicated because the settlement of the raft is affected by the presence of the piles and because a piled raft foundation consists of conventional piles and a rigid raft, as shown in Figure 5.10. Considering each of these foundation elements separately leads to the conclusion that interaction is inevitable. The mat alone is certainly affected by the presence of the piles because the foundation is much stiffer than with the soil alone. The piles alone are affected by the earth pressure from the raft because the increased lateral stresses on the piles affect the capacity for side resistance. The problem can be solved by using the finite-element method, where appropriate plate or solid elements can be used for modeling the raft. Beam elements can be used for modeling piles. The soil around the piled raft system can be conveniently modeled as solid elements. Modeling the problem by the finite-element method, which is widely available, was found to be practical and yielded reasonable agreement between results from analyses and from experiments (Novak et al., 2005).

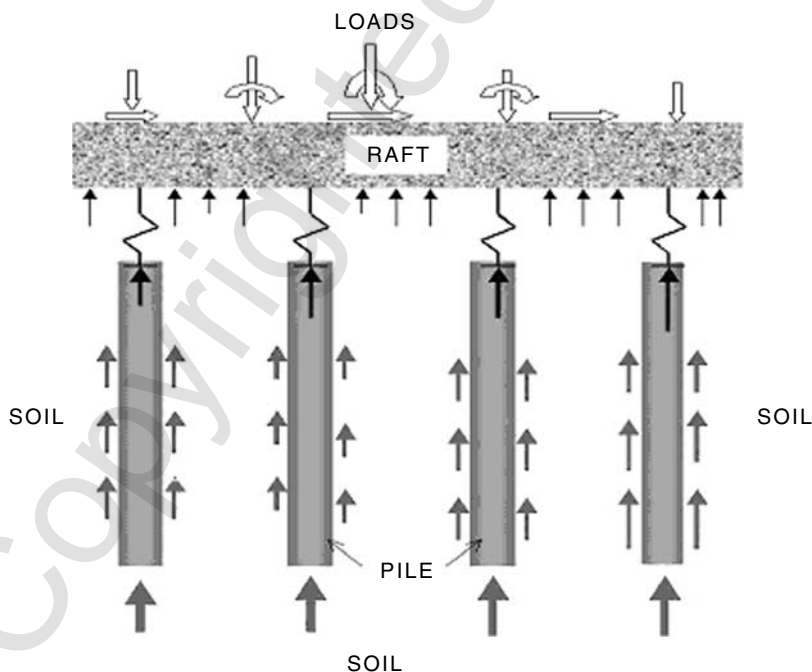


Figure 5.10 Soil–structure interaction of a piled raft structure.

PROBLEMS

- P5.1.** (a) Nine items were listed for the selection of the pile type and hammer for a particular project. You are the geotechnical engineer. List the items to be obtained from the owner, from the structural engineer, and by you. (b) Of the nine items, which one is most important to the geotechnical engineer and why?
- P5.2.** In addition to performing an appropriate subsurface investigation, if you are responsible for using a new and innovative type of deep foundation that would save the owner substantial money, what three steps in what order would you take to ensure construction of high quality?
- P5.3.** Name two factors that would lead you to select a deep foundation instead of a shallow foundation for a project even though strong soil exists at the ground surface